Design of a Low-Cost Fiber Optical Occlusion Based Automatic Tool Setter for Micro Milling Machine

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ABSTRACT

The objective of this research is to create an inexpensive, automated tool setter to reduce the overall tool set up time. The project focused on addressing the tool setting in the Z-axis (spindle axis), which is needed for each tool change, and accounts for majority of the total tool setting time. A fiber optic FS-V30M sensor from Keyence that is equipped with a light emitting element and receiving sensor was used. The sensor detects the position of the micro-tool by measuring the light intensity change as the tool crosses the emitted light beam. A bracket was designed and manufactured to mount the sensor onto the workpiece pallet to hold the fiber optic cable. A novel search/detection algorithm was developed and implemented in the CNC machine controller. Controlled experiments were conducted to test the performance of the tool setter. The system achieved 0.6 μm repeatability and 2 μm accuracy across different size of micro-tools. The execution of each tool setting takes about 10 seconds, which is a 80%~90% reduction from the manual tool setting.

1. INTRODUCTION

In response to the rising demands of miniature components, a tremendous amount of research and development work has centered on developing innovative manufacturing equipment and processes for cost-effective manufacture of small precision parts, especially those involving complex 3D geometry. Micro-mechanical machining with miniature machine tool (mMT) is such an emerging technology, which offers many advantages over conventional machines including significantly reduced cost, space, and energy consumption [1-4].

Due to the small size of the tool used in the micro-machining operations, tool setting is one of the most challenge and time-consuming jobs. The diameter of a typical micro-endmill are in the range of 50~500 μm, which can be barely seen with naked eyes. The current practice is to bring the micro-tool gradually approaching the workpiece surface with the hand-wheel and monitor the process through a magnifying lens, once the micro-tool touches the surface, the operator will set the current machine location as zero location in Z axis (along the tool axis). This manual process is not only tedious but also time-consuming. Consider a typical machining part with features on both sides, a minimum of two fixture setups are needed to complete manufacturing. For each fixture, the machining sequence normally consists of three stages: roughing, semi-finishing, and finishing, and each stage involves at least one tool change and one tool setting. Therefore, it is common to have a total of six tool changings/settings for each part. Assuming each manual tool setting takes 3 minutes, the total tool changing/setting time can be up to be 20 minutes. This time frame accounts for roughly 20-40% of the total machining time. Furthermore, fragile micro-tools are susceptible to breakage with the manual tool setting due to the contact between the tool and the workpiece. A non-contact automatic tool setting system is desirable to improve the tool setting process.

The non-contact automatic tool setter for conventional machine tools are commercially available from several vendors, such as Blum Micro Compact EC[5], Renishaw NC4[6]. But none of the systems in market place are small enough to be adopted in the micro-machine tools. The objective of this research is to develop an inexpensive automatic tool setter for micro-milling machine so that tool setup time can be significantly reduced. The remainder of the paper is organized as follows. Section 2 presents the system design and operating principle. Section 3 discusses the tool tip detection algorithm. The experimentation results of system repeatability and accuracy is presented in Section 4.

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2. SYSTEM DESIGN AND OPERATING PRINCIPLE

The goal of tool setting is to establish workpiece coordinate origin for tools with different lengths so that for any given tool, the zero Z coordinate corresponds to the location where the tool tip touches the reference surface on the workpiece. A tool setter is a device that is designed to facility the tool setting process. It is fixed on the machine, and contains a sensing unit to detect the location of the tool tip. The sensing unit replaces the reference surface to register the location of the tool so that the contact between the tool tip and the reference surface can be avoided during the tool setting process. This is especially beneficial in micro-machining since the micro-tools are usually very fragile.

In this work, the tool setter was designed and implemented on Microlution S310 3-axis horizontal micro-milling machine. The machine has a working volume of 60X60X250 mm driven by linear motors with the encoder resolution of 20 nm in each axis. The machine coordinate system is shown in the figure. The main component of the tool setter is a fiber optical thrubeam type sensor Keyence FS-V30M. The sensor costs less than \$200, which is about 3%~5% of a commercial tool setter's cost. It also has very small size and high spatial resolution and sensitivity. All are desirable properties for a confined space of a micro-milling machine. The sensor emits a light beam from its light-emitting element, and the receiver side of the sensor converts the light intensity received proportionally to an electric voltage. This sensor will detect an object (micro-tool) when it crosses the optical axis between the transmitter and the receiver since the light intensity will have a measurable decrease. The smallest detectable object is 5 μm, which is perfect for detecting the micro-tools. The fiber cables are 1 mm in diameter and were fixed on the mounting bracket using set screws. The through holes on both sides of the mounting bracket were drilled in the same drilling cycle to ensure the receiver and the transmitter is co-axial. The mounting bracket was fixed on a designated base plate of workpiece pallet. Figure 1 shows the system configuration of the fiber optical occlusion tool setter.

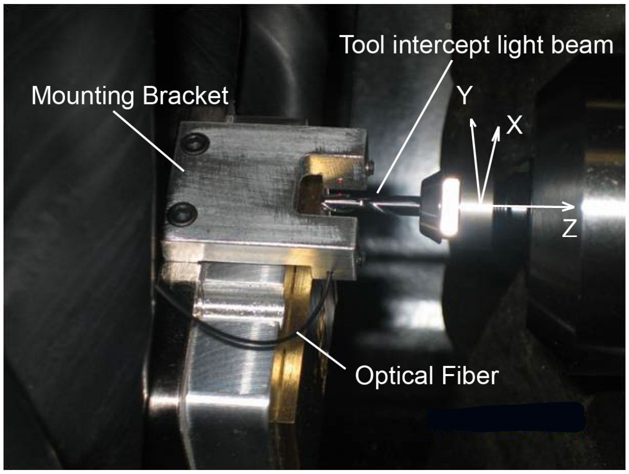

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Figure 1. System configuration of the fiber optical occlusion tool setter.

The analog measurement of the light intensity in voltage was gathered by the machine controller (DeltaTau Turbo PMAC2) through an A/D converter. The collected data were then used to trigger tool tip detection.

For a micro-machining job, the tool setting process using the non-contact automatic tool setter involves the following steps. First, a probe (can be an endmill with a relatively large diameter, e.g., 500 μm) is used to measure the displacement (*d*) between the edge of the light beam and the reference surface of the workpiece in the Z direction. This displacement is measured by recording the encoder readings when the probe is on the edge of the light beam (*z1*) and when the probe touches the reference surface (*z2*). The difference between *z2* and *z1* is the displacement (*d*). This displacement (*d*) is fixed for a given workpiece and is stored in the machine memory once the measurement is done. Second, the probe is taken out from the spindle and a new tool is installed. The new tool tip will be brought to the edge of the light beam and the corresponding encoder reading of Z axis (*z3*) will be recorded. Finally, the proper Z axis zero (tool tip align with the reference surface) will be established by offseting the distance *d* from *z3*. It is evident that the most crucial step in tool setting is to detect the tool tip location using the fiber optical sensor. The tool tip detection procedure and algorithms will be discussed in detail in the next section.

3. TOOL TIP DETECTION ALGORITHMS

3.1. WHITE NOISE ANALYSIS OF THE SENSOR SIGNAL

In order to set the threshold for tool tip detection, it is necessary to know the magnitude of the noise and the resolution of the sensor. The presence of significant noise in the signal is a consequence of using a relatively cheap light emitting sensor instead of a laser sensor. The high rotational speed of the micro-milling machine spindle also amplifies noise in the sensor's output signal [7]. Therefore we decided to run the tool setting process when the tool was at rest. Figure 2 shows an example of the white noise at full light intensity with nothing between the receiver and the transmitter. The noise was primarily reflected as periodical spikes. This noise can be detrimental to the tool setting process by affecting the robustness of the search algorithm. The frequency and duration of the spikes were found to be consistent over time. The time between each instance of spike is approximately 0.2 seconds (5 Hz) and each instance has duration of about 0.04 seconds. The full light intensity is converted to around 1.62V and the magnitude of the spike is about 0.02V in magnitude. In order to achieve robust edge detection, the spike in the signal should be filtered before a threshold based algorithm can be applied. To this end, we organized the original data into consecutive samples; each sample consists of data collected within duration of 0.04s. At a sampling frequency of 500 Hz, each sample consists of 20 consecutive measurements. The spike in the original signal was diminished down to below 0.004V in magnitude in the sample mean as shown in Figure 2. The sample mean can be considered as a low passing filter. If we use the sample mean for the tool tip detection, the algorithm will be much more robust. Furthermore, a sample range based outlier discriminator will be used to further filter out the samples containing spikes.

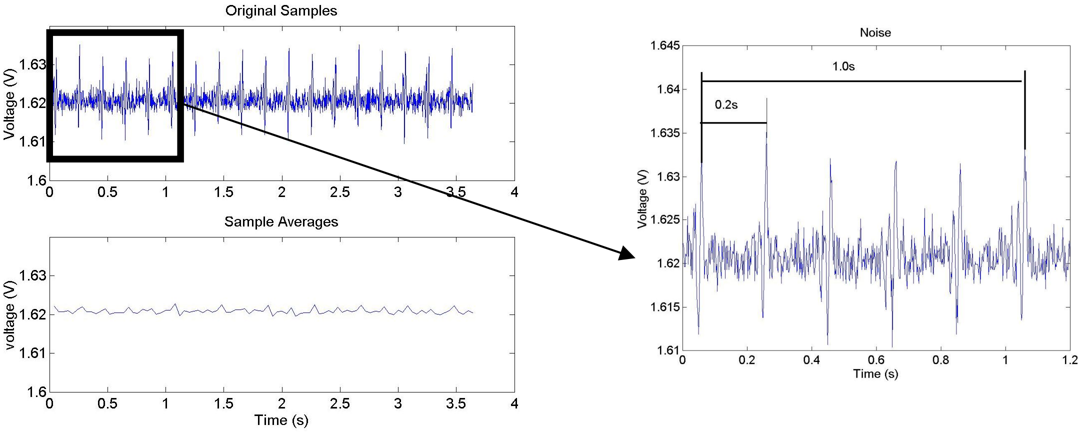


Figure 2. White noise present in sensor signal.

3.2. SENSOR SENSITIVITY OF OPTICAL OCCLUSION

A micro-endmill with a diameter of 100 μm was used to test the sensitivity of the optical occlusion. The initial test was performed to ensure the tool axis and the center of the light beam fall into the same XZ plane, and tool cut halfway into the light beam similar to the case shown in Figure 1. As the tool starts to back off along the Z axis, the occlusion of the optical beam gradually decreases; the light intensity increases, causing the output voltage to increase. Both the encoder reading of the Z axis and the senor output voltage were collected using the motion controller and plotted in Figure 3. It can be clearly seen that the there is a significant output voltage of around 1.08V even when the tool was fully immerged in the way of the light beam, suggesting that the diameter of the light beam is larger than the diameter of the tool used. The overall voltage change from full occlusion to no blocking (full light intensity) is about 0.54V. According to the sensor specification, the minimum detectable object is 5 microns in diameter. For a 100 micron diameter tool, it is expected that a depth of sub-micron immersion into the beam should be readily detectable.

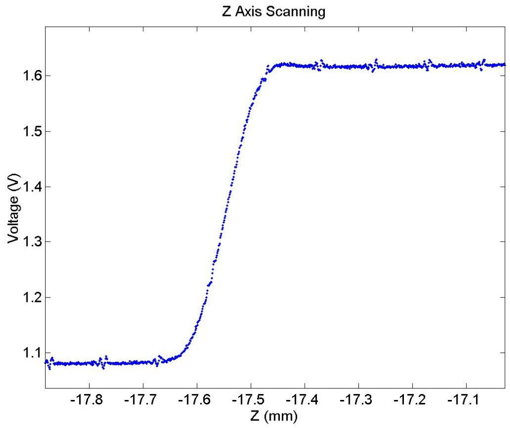


Figure 3. Sensitivity of optical occlusion from a micro-endmill of 100 μm in diameter.

3.3. TOOL TIP DETECTION PROCEDURE

The tool tip detection by the fiber optical sensor is the most critical step in tool setting. The procedure is depicted in Figure 4. Before the process starts, some preparation is needed. This includes collecting full light intensity data at the sampling frequency of 500 Hz in real time for a period of one second and computing the grand mean of the output voltage V_0, and the maximum sample range R_{max}, where the sample size was set to be 20 (corresponding to duration of 0.04s). The sample size was determined by the duration of the spike in the white noise. The R_{max} will later be used to reject the samples containing noisy spikes. The XY axes also rapidly move to the location where the tool center and the light beam are aligned properly in the same XZ plane.

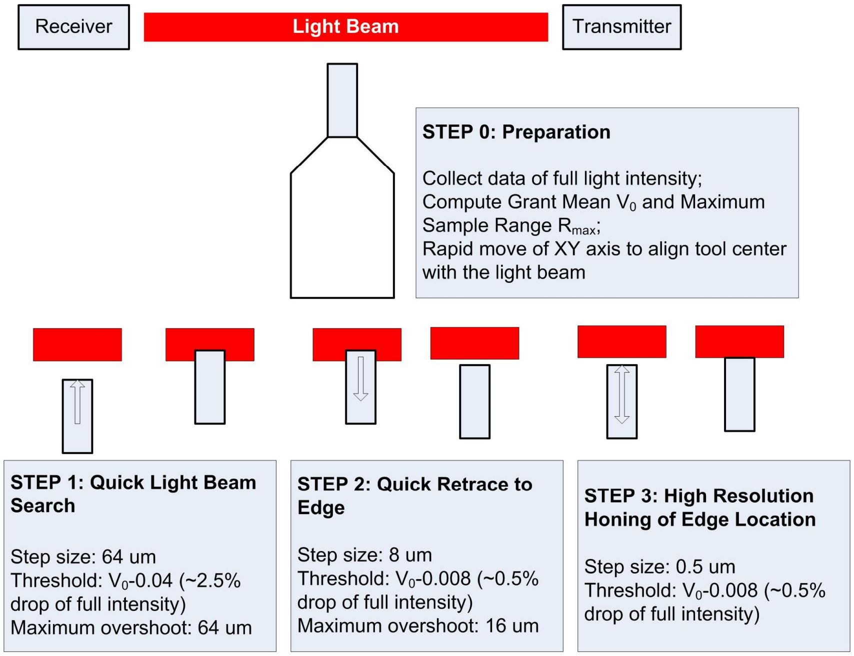


Figure 4. Flow chart of the edge search/detection algorithm.

Once the preparation step is done, the quick light beam search starts. The tool approaches the light beam at a fast rate in a few steps. The step size is set at 64 μm. At the end of each step, five light intensity samples (with same sample size of 20) will be collected by the motion controller. The sample range will be computed and compared with the R_{max}, if it exceeds 50% of R_{max}, the sample is discarded. This is a range based on the outlier discriminator to clean the original data. The grand mean of the sample mean of the valid samples will then be computed and compared to the threshold of

V_0-0.04, which corresponds to about 2.5% drop of full light intensity. If the grand mean is lower than the threshold value, the tool will stop. At this time, the tool should already intercept the beam. Then the tool retreats at a reduced step size of 16 μm until the light intensity recovers to above V_0-0.008, which is about 99.5% of full light intensity. Now the tool should be within a few microns from the edge of the light beam. Finally, the high resolution honing of the edge detection starts, with the tool first moving into the beam for a fixed distance of 16 μm to compensate the possible overshoot from previous step and then retracing back with a much finer step size of 0.5 μm. The threshold will stay the same as in the previous step, i.e., until the light intensity recovers back to at least 99.5% of the full intensity. These reciprocal motions allow the machine to hone very precisely on the edge of the light beam with high efficiency and repeatability. The entire process takes about 10s to complete.

The algorithm was implemented in the motion controller as a special program. The program can be called using a designated preparatory G-code (G65).

4. EXPERIMENTATION

Experiments were performed to measure the repeatability of the tool tip detection and the tool setting accuracy in real micro-machining setting was experimentally characterized.

4.1. REPEATABILITY OF TOOL TIP DETECTION

Two micro-endmills with diameters of 100 μm and 500 μm were used for the experiments. Five trails of tool tip detection were conducted for each tool from arbitrary starting points. The data summarized in Table 1 are the final Z locations when the tool tip detection completed. It is observed that the repeatability of the tool with larger diameter of 500 μm is significantly better than the one with smaller diameter of 100 μm. The pooled standard deviation of tool location was 0.301 μm, which gave a 2σ repeatability of 0.602 μm across different tools. The repeatability is comparable to the commercially available tool setters (such as such as Blum Micro Compact EC [5], Renishaw NC4 [6]) which claim to have a 2σ repeatability of 0.1 μm. More importantly, the high repeatability was achieved for only a fraction of the cost.

Table 1. Repeatability of tool tip detection algorithm.

	Z value at the end the tool tip detection (mm)					Standard Deviation (mm)	Repeatability (μm)
Tool #1 (500 μm)	-27.8371	-27.8371	-27.8373	-27.8372	-27.8371	8.9442E-05	0.179
Tool #2 (100 μm)	-28.4552	-28.4553	-28.4543	-28.4552	-28.4552	4.1593E-04	0.832
				Pooled Standard Deviation σ			0.301
				2 σ Repeatability			0.602

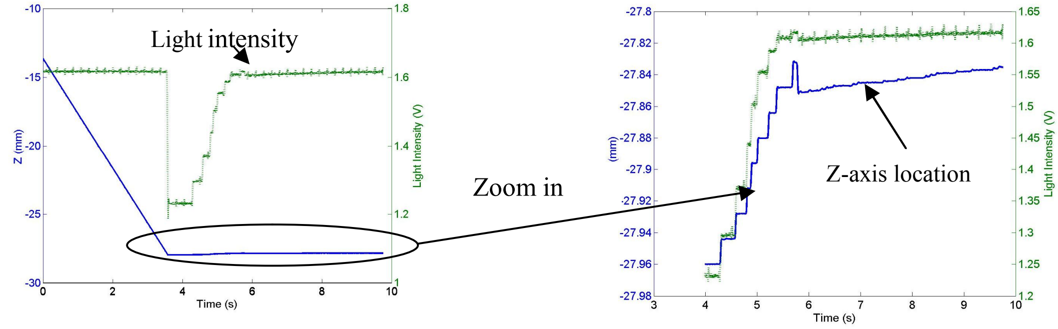
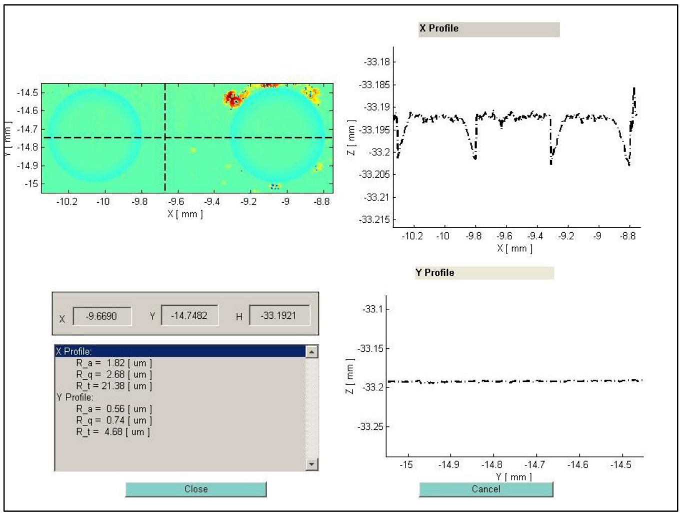


Figure 5. Light intensity change in the tool tip detection process.

Figure 5 shows a graphical view of the tool tip detection algorithm in action. As the tool travels in toward the light beam, the Z axis location line has an apparent downward slope. When the tool crosses the light beam and the light intensity decreases, the tool begins to retrace back. This step is so subtle that the graph had to be zoomed in (right graph). The graph clearly shows how the high resolution edge detection procedure finds the exact edge of the light beam with in-and-out motion.

4.2. TOOL SETTING ACCURACY IN REAL MICRO-MACHINING SETTING

In order to test the accuracy of the tool setter in an actual micro-machining process, two shallow holes of identical programmed depth of 10 μm were created on a flat reference surface of the workpiece with a 500 μm micro-endmills in two separate tool setups. First the tool was also used as a probe to establish the Z displacement between the edge of the light beam and the reference surface, and the first hole was milled. The tool was removed from the spindle after the first cut. Then the tool was re-chucked to the spindle, and the tool tip detection procedure was performed, combined with the displacement found in the first setup, the Z origin was re-established for the tool. A second hole was milled on the same reference surface. If there is an error in the tool setting procedure, the machined holes will end up with different depths. The difference will be the upper bound of the error. The two holes were examined with on-the-machine scanning microscope [8]. Data collected from the surface scan indicated roughly a 2 μm difference in the depth as shown in Figure 6. The result proves that the tool setting accuracy is within 2 μm, which is satisfactory for most of micro-machining applications.



X -9.6690 Y -14.7482 H -33.1921

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X Profile:
      R_a =  1.82 [ um ]
      R_q =  2.68 [ um ]
      R_t = 21.38 [ um ]
Y Profile:
      R_a =  0.56 [ um ]
      R_q =  0.74 [ um ]
      R_t =  4.68 [ um ]
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Figure 6. Tool setting accuracy (difference in depth of two holes with equally set depth).

5. CONCLUSIONS

The following conclusion can be made from the project:

1) A fiber optic sensor Keyence FS-V30M was selected to build the non-contact tool setter for the micro-milling machine. The sensor emits a light beam from its light-emitting element. On the receiving side, the sensor measures the change in the light intensity caused by the target (micro-tool) crossing the optical axis. The smallest detectable object is 5 μm, which is sufficient for micro-tool detection (50 μm ~ 500 μm).

2) A novel edge detection and search algorithm was developed to accurately locate the edge of the emitted light beam in the presence of significant noise. The influence of the noise was minimized through averaging. Furthermore, a sample range based outlier discriminator was used to take the noise data out.

3) The algorithm was implemented in the CNC machine controller for tool setting. The system achieved 0.6 μm repeatability for across different tools and an accuracy of 2 μm in the actual micro-machining setup. The tool setting takes about 10 second, which is 80%~90% reduction from manual tool setting based on a time study.

ACKNOWLEDGEMENTS

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